

POTENTIAL CO₂ STORAGE CAPACITY OF THE SALINE PORTIONS OF THE LOWER CRETACEOUS AQUIFER SYSTEM IN THE PCOR PARTNERSHIP REGION

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EXECUTIVE SUMMARY

A large, Lower Cretaceous age, regional aquifer system underlies much of the central portion of the North American continent, including the Plains CO₂ Reduction (PCOR) Partnership region. The Lower Cretaceous aquifer system is complex, but with respect to CO₂ sequestration potential, it may be one of the most important aquifers in the region. Water quality varies greatly in the system, ranging from saline to fresh. Obviously only the saline parts of the formation would be considered for CO₂ sequestration. The U.S. Geological Survey (USGS) and others recognize two discrete clastic aquifers within the Lower Cretaceous. They are separated throughout part of the PCOR Partnership area by shale. Where the shale is absent, the aquifers merge and are considered a single aquifer. This aquifer system has significant regional sequestration potential.

ACKNOWLEDGMENTS

The PCOR Partnership is a collaborative effort of public and private sector stakeholders working toward a better understanding of the technical and economic feasibility of capturing and storing (sequestering) anthropogenic

carbon dioxide (CO₂) emissions from stationary sources in the central interior of North America. It is one of seven regional partnerships funded by the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnership (RCSP) Program. The Energy & Environmental Research Center (EERC) would like to thank the following partners who provided funding, data, guidance, and/or experience to support the PCOR Partnership:

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BACKGROUND/INTRODUCTION

PCOR Partnership Background

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains CO₂ Reduction (PCOR) Partnership is working to identify cost-effective CO₂ sequestration systems for the PCOR Partnership region and, in future efforts, to facilitate and manage the future demonstration and deployment of these technologies. In this phase of the project, the PCOR Partnership is characterizing the technical issues, enhancing the public's understanding of carbon dioxide (CO₂) sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for the demonstration of regional CO₂ sequestration opportunities.

There is concern that the ongoing accumulation of CO₂ and other greenhouse gases in the atmosphere from human activity will affect global climate. CO₂ is a major by-product of energy use. CO₂ sequestration means capturing CO₂ and putting it into environmentally sound temporary or permanent storage. Indirect sequestration involves enhancing the natural uptake of CO₂ from the air and storing it for some period of time in soils or vegetation. Direct sequestration involves capturing CO₂ at a source before it can be emitted to the atmosphere. The most efficient concept would capture CO₂ at large stationary sources like factories or power plants and then inject the CO₂ into secure storage zones deep underground (geologic sequestration). The injection and control of CO₂ in underground formations has been done safely for more than 30 years by oil companies. The latter of these forms of sequestration is the focus of this discussion.

This report focuses on briefly describing the Lower Cretaceous aquifer system in the PCOR Partnership area. Using published geological data, a reconnaissance

sequestration volume has been calculated for a portion of the PCOR Partnership area.

The geology of CO₂ sequestration is essentially the geology of petroleum exploration; the search for oil is the search for sequestered hydrocarbons. Therefore, the geological conditions that are conducive to hydrocarbon sequestration are also among the most favorable conditions for CO₂ sequestration. The three requirements for sequestering hydrocarbons are a hydrocarbon source, a suitable reservoir, and an impermeable trap. These requirements are the same as for sequestering CO₂, except that the source is anthropogenic and the reservoir is referred to as a sink.

Introduction

The PCOR Partnership region includes several sedimentary basins, some of which have significant potential as geological sinks for sequestering CO₂. Geological sinks that may be suitable for long-term sequestration of CO₂ include both active and depleted petroleum reservoirs, deep saline formations, and coal seams, all of which are common in these basins. The Lower Cretaceous aquifer systems within six of these basins were examined for CO₂ storage potential as part of Phase I. The basins examined and discussed in this topical report are the Williston, Powder River, Alberta Basin, the Denver–Julesberg, the Kennedy, and the Salina. Portions of Iowa and Minnesota also contain the same aquifer-bearing Lower Cretaceous formations and were, therefore, also examined.

Although the names of the formations may vary between the states and provinces, the system of deposition and general lithology are consistent. In general, the Lower Cretaceous aquifer system comprises an upper and lower clastic aquifer which is separated by an impermeable shale. The presence of the shale is not ubiquitous throughout the PCOR Partnership area. Where it is absent, the upper and lower

aquifers are not differentiated but are treated as a single aquifer unit.

To catalog the groundwater resources of the United States, the U.S. Geological Survey (USGS) has subdivided the U.S. into a series of 13 geographic segments that were compiled into a national groundwater atlas (various dates). The principal aquifer systems of each segment were then detailed in a series of studies. These studies, along with papers published by the Alberta Geological Survey, were the primary sources of information regarding the nature of the Lower Cretaceous aquifer system.

Segment 1 of the USGS Groundwater Atlas includes the Williston Basin and the Powder River Basin and is represented by the states of Montana, Wyoming, North Dakota, and South Dakota. The USGS refers to this segment as the northern Great Plains aquifer system. The formations that make up the Lower Cretaceous portion of the northern Great Plains aquifer system are, in descending order, the Newcastle, Skull Creek, and Inyan Kara in North Dakota (Bluemle et al., 1986) and northeastern Wyoming; the Muddy, Skull Creek, Fall River Sandstone, and Kootenai in eastern Montana (Condon, 2000); and the Newcastle sandstone, Skull Creek Shale, and Inyan Kara in South Dakota (Schoon, 1974).

Segment 3 of the USGS Groundwater Atlas includes Kansas, Missouri, and Nebraska. The state of Nebraska includes portions of the Denver–Julesberg Basin, Kennedy Basin, and Salina Basin and is considered by USGS to be part of the Great Plains aquifer system. This paper examines the Nebraska portion of Segment 3. The formations making up the Lower Cretaceous portion of the Great Plains aquifer system are, in descending order, the Maha (equivalent to Newcastle), Apishapa Confining Unit (equivalent to the Skull Creek), and Apishapa (equivalent to Inyan Kara).

Segment 9 of the USGS Groundwater Atlas includes Michigan, Wisconsin, Minnesota, and Iowa. This paper examines the Iowa and Minnesota portions of Segment 9. In Iowa and Minnesota, there is no Skull Creek Formation equivalent section, and only a single sand interval, the Dakota Formation, is recognized (Anderson and Ruhl, 1984; Iowa Geological Survey, 2005).

In Canada (the Canadian portion of the Williston Basin and the Alberta Basin), the Viking, Joli Fou, and Mannville Formations are equivalent to the Newcastle, Skull Creek, and Inyan Kara, respectively. The Alberta Geological Survey provided data for this portion of the region.

Nomenclature

To conduct a reconnaissance-level evaluation of the potential CO₂ storage capacity of the Lower Cretaceous aquifer system, it was necessary to simplify the geohydrologic stratigraphy of the region. Table 1 illustrates the stratigraphic relationship of the formations comprising the Lower Cretaceous aquifer unit in the four study areas of the PCOR Partnership region. The Inyan Kara and equivalents (of USGS Segment 1), the Apishapa (of USGS Segment 3), and the Mannville (Canada) are temporally and laterally equivalent formations and will be informally referred to in this paper as the Lower Aquifer Unit. Likewise, the Skull Creek (of Segment 1), the Apishapa Confining Unit (of Segment 3), and the Joli Fou (Canada) are laterally and temporally equivalent shales and will be informally referred to as the Middle Aquitard Unit. At the top of the system, the Newcastle and equivalents (of USGS Segment 1), the Maha (of USGS Segment 3), and the Viking (Canada) are laterally and temporally equivalent sandstones that are informally referred to as the Upper Aquifer Unit.

Table 1. Stratigraphic Relationships of the Lower Cretaceous Geohydrologic System Throughout the PCOR Partnership Region

Minnesota/Iowa (Segment 9)	Northern Great Plains (Segment 1)	Great Plains (Segment 3)	Canada	Regional Designation	Lower Cretaceous System
Dakota	Newcastle	Maha	Viking	Upper Aquifer Unit	
Dakota	Skull Creek	Apishapa Confining Unit	Joli Fou	Middle Aquitard Unit	
Dakota	Inyan Kara	Apishapa	Mannville	Lower Aquifer Unit	

In Minnesota and Iowa (USGS Segment 9), the Lower Cretaceous aquifer extends beyond the depositional extent of the Skull Creek shale. With the Skull Creek shale missing, the sandstones that are equivalent to the Lower and Upper Aquifer Units defined above have merged into a single sandstone body, known as the Dakota Formation. The depth of the Dakota Formation in Minnesota and Iowa is never greater than 2000 feet and is, therefore, incapable of maintaining CO₂ in a supercritical state. The Dakota Formation is also a significant source of water in Minnesota and Iowa. Because of these aspects, the Minnesota and Iowa portions of the Lower Cretaceous aquifer system are not suitable candidates for large-scale CO₂ sequestration and will not be described further in this report.

Geology of the Lower Cretaceous System

Reviewing the tectonic origin and structure of a basin, as well as its hydrogeology and geology, including the petroleum geology, can lend valuable insights in any attempt to identify geological sinks for CO₂ sequestration in a sedimentary basin.

Sedimentation occurred throughout most of the PCOR Partnership region during the Cretaceous Period. Deposition was widespread and associated with a large north-south trending epicontinental

seaway that covered much of the central North American craton, stretching from Alaska to the Gulf of Mexico (Figure 1). The sequence of Lower Cretaceous sediments that occur in the PCOR Partnership region were deposited in a series of large-scale transgressive and regressive cycles. The sediments are clastic and represent depositional environments that include marine, transitional marine, and nonmarine conditions. The stratigraphy and hydrogeologic characteristics of the three general units that comprise the Lower Cretaceous system are widely variable across the region, but there are many locations where the conditions of the aquifer may be amenable to long-term CO₂ storage.

Understanding the basic hydrogeologic characteristics of an aquifer is critical to evaluating its potential use as an injection target for CO₂ sequestration. Key characteristics that must be considered as part of a thorough evaluation include aquifer thickness, confining unit (seal) thickness, groundwater flow rates, flow direction, and the locations of recharge and discharge areas. The following is a generalized description of the units that comprise the Lower Cretaceous aquifer system in the PCOR Partnership region.



Figure 1. Extent of the Cretaceous Seaway in North America (Rice and Shurr, 1980).

General Flow Conditions of the Lower Cretaceous Aquifer System

Recharge of the Lower Cretaceous aquifer system in the Dakotas, eastern Montana, and northeastern Wyoming occurs in highland areas to the west, specifically the Rocky Mountains and the Black Hills. Recharge for the Canadian portion of the region also occurs in the Rocky Mountains. Significant recharge in the Dakotas and eastern Montana has also been documented to occur from underlying strata, including the Cambrian-Ordovician and the Mississippian Madison aquifer systems (USGS PP 1402; Case, 1984; Bachu and Hitchon, 1996). The recharge area for the Nebraska portion of the Lower Cretaceous aquifer system is found in southeastern Colorado (USGS Groundwater Atlas, 2004).

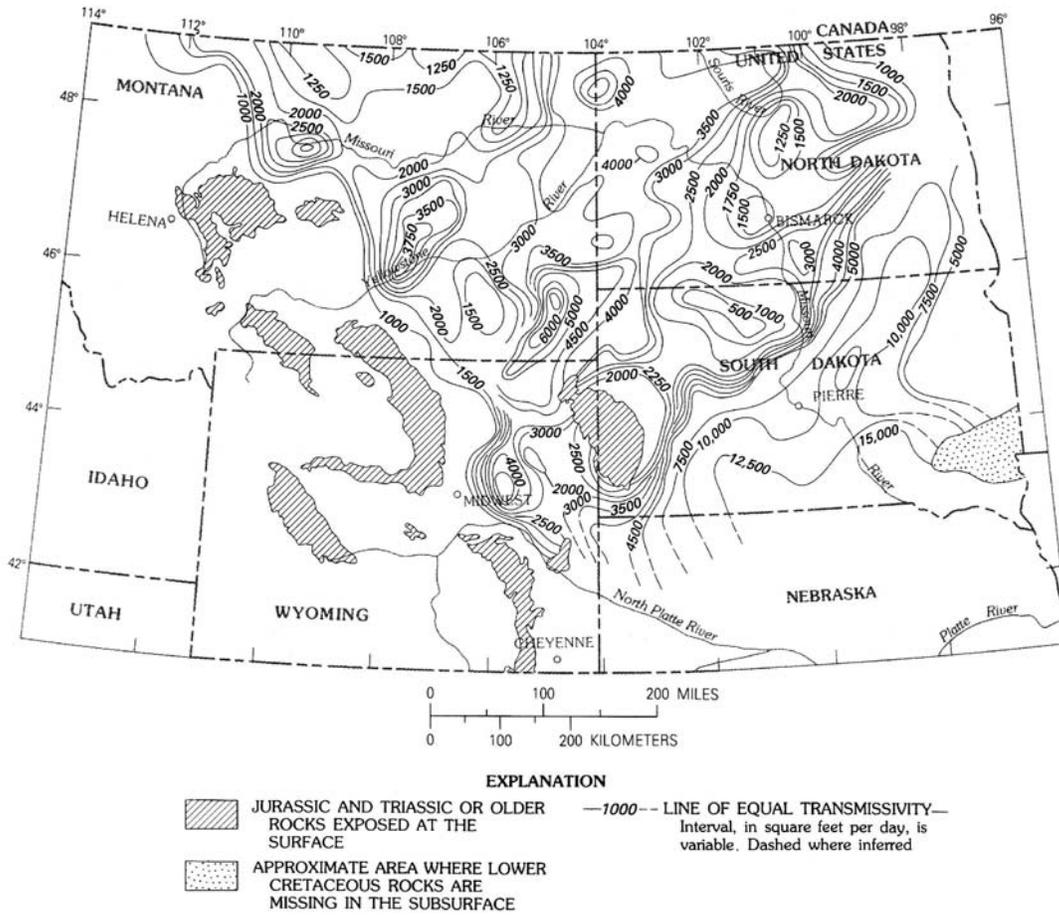
The USGS (USGS PP 1402) prepared a simulation model for the Lower Cretaceous aquifer system in the Dakotas, Montana, and Wyoming. However, the model did not differentiate between the Upper, Middle, and Lower Units. In the USGS model, transmissivity was calculated for the aquifer (Figure 2). Transmissivity (the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient) was shown to be widely variable, ranging from approximately 1000 ft²/day to approximately 15,000 ft²/day. The model also calculated vertical hydraulic conductivity of the overlying confining unit (Figure 3). Vertical conductivity of the confining unit was shown to range from less than 5 to greater than 10 ft/day × 10⁻⁴.

Some of the aquifers in the system subcrop in the east (Figure 4). Injection sites would have to be located at distances sufficiently removed from the subcrop (based on groundwater flow direction and velocity) to prevent leakage of CO₂ to the surface. Further studies of the local hydrodynamic regime would need to be conducted in the areas where CO₂ injection may be considered.

CO₂ can be sequestered by three primary mechanisms; 1) solubility trapping through dissolution in the formation water; 2) mineral trapping through geochemical reactions with formation water and rocks; and 3) hydrodynamic trapping of a CO₂ plume. Thus the capacity of a brine formation may be considered in terms of free-phase CO₂ in the rock pore space, dissolved-phase CO₂ in the formation water, and CO₂ converted to solid minerals that become part of the rock matrix. The degree to which each mechanism will affect sequestration under the range of geologic, hydrodynamic, and geochemical conditions that can occur in any given field is currently not well understood and difficult to predict. It is possible, and perhaps even likely, that all three mechanisms may occur at any given location. Mineral trapping is the least understood.

Since the focus of Phase I of the PCOR Partnership was to conduct reconnaissance-level evaluations of geologic sinks in the region, capacity estimates for brine formations only considered characteristics that control solubility and hydrodynamic trapping mechanisms. Mineral trapping was not considered, and the effects that it may have on the sequestration of CO₂ in the studied formations, whether they be positive or negative, are unknown.

CO₂ dissolved in aqueous solution would be expected to migrate in the general directions of groundwater flow. Flow direction of the Lower Cretaceous aquifer system is generally to the east, northeast in the northern U.S. portion of the region (Figure 5). In the southern portion of the region, water flows (Figure 6) to discharge areas in central Kansas and Nebraska. The sandstone of the Upper Aquifer Unit in Nebraska outcrops at the surface along the bluffs of the Missouri River Valley between the towns of Blair and Ponca, Nebraska. In Alberta and southwestern Saskatchewan (Figure 7), the system exhibits an easterly and southeasterly flow (Bachu and Hitchon, 1996).



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Transmissivity distribution used in the Lower Cretaceous aquifer simulations.

Figure 2. Transmissivity of the Lower Cretaceous aquifer system in the northern Great Plains.

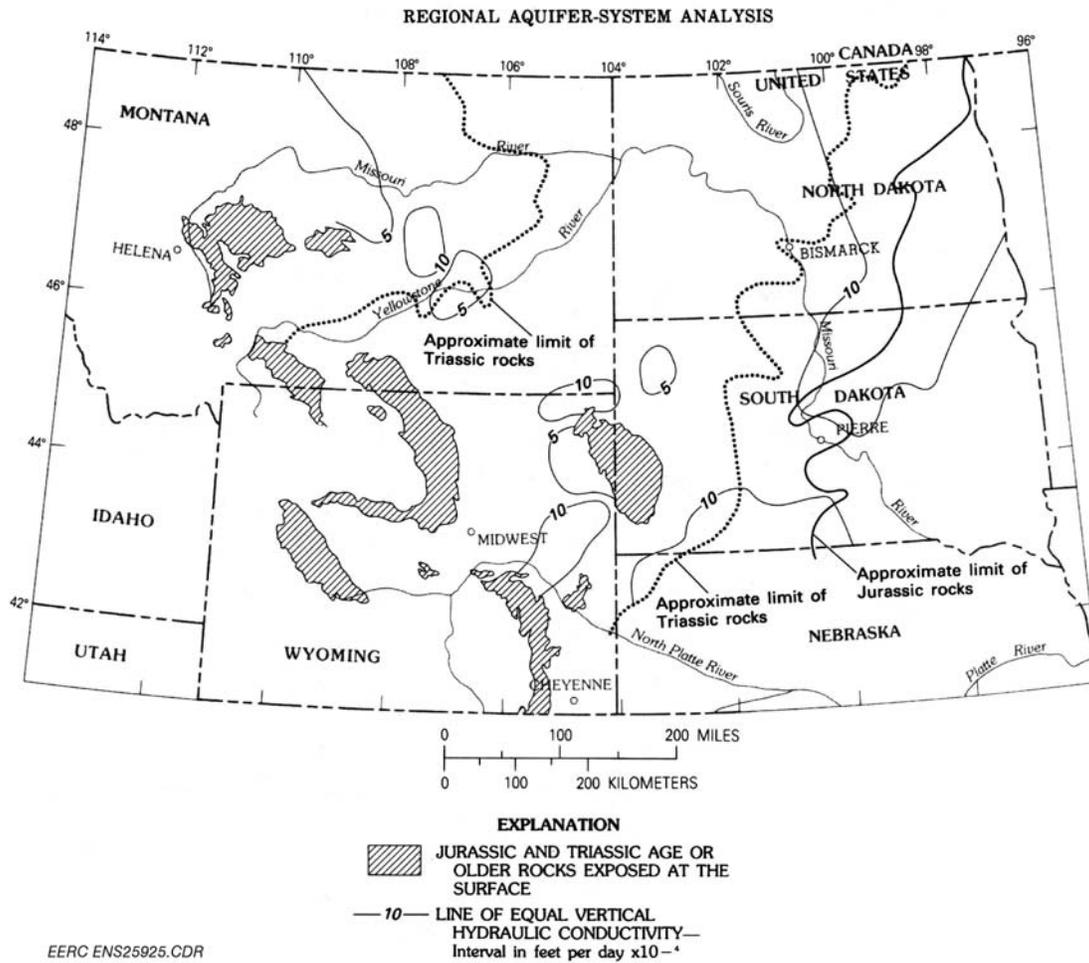


Figure 3. Vertical hydraulic conductivity of the overlying confining unit: Lower Cretaceous aquifer system in the northern Great Plains.

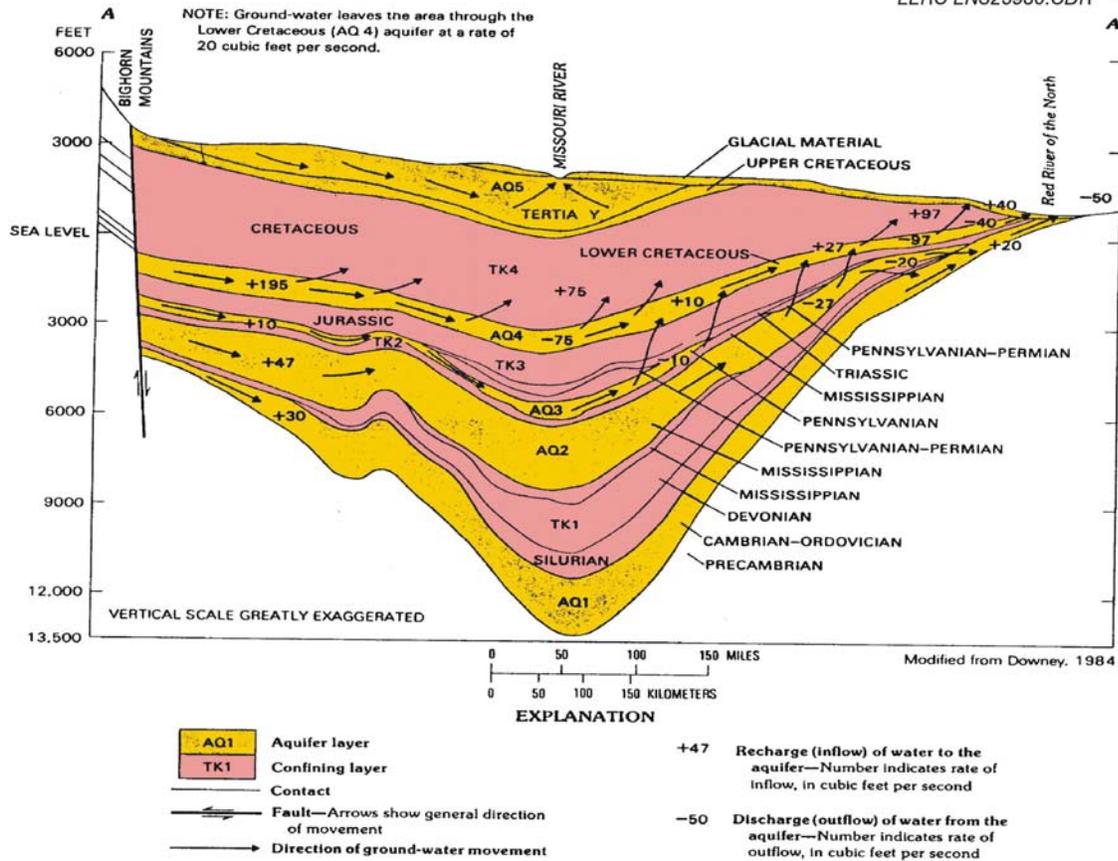
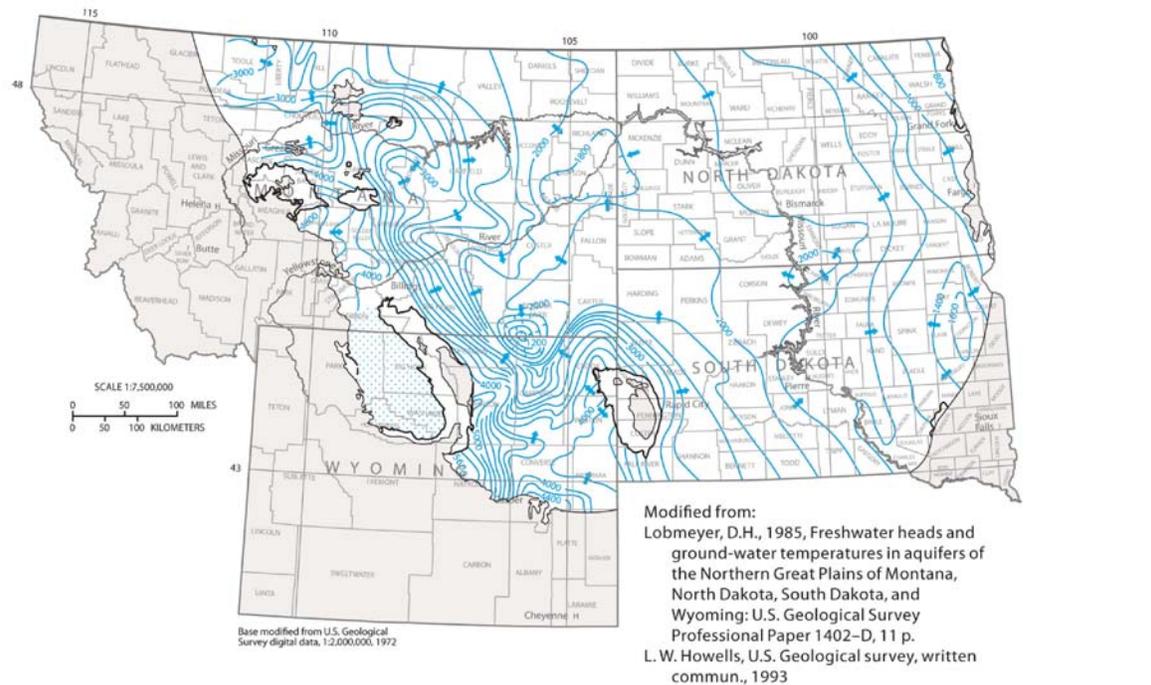


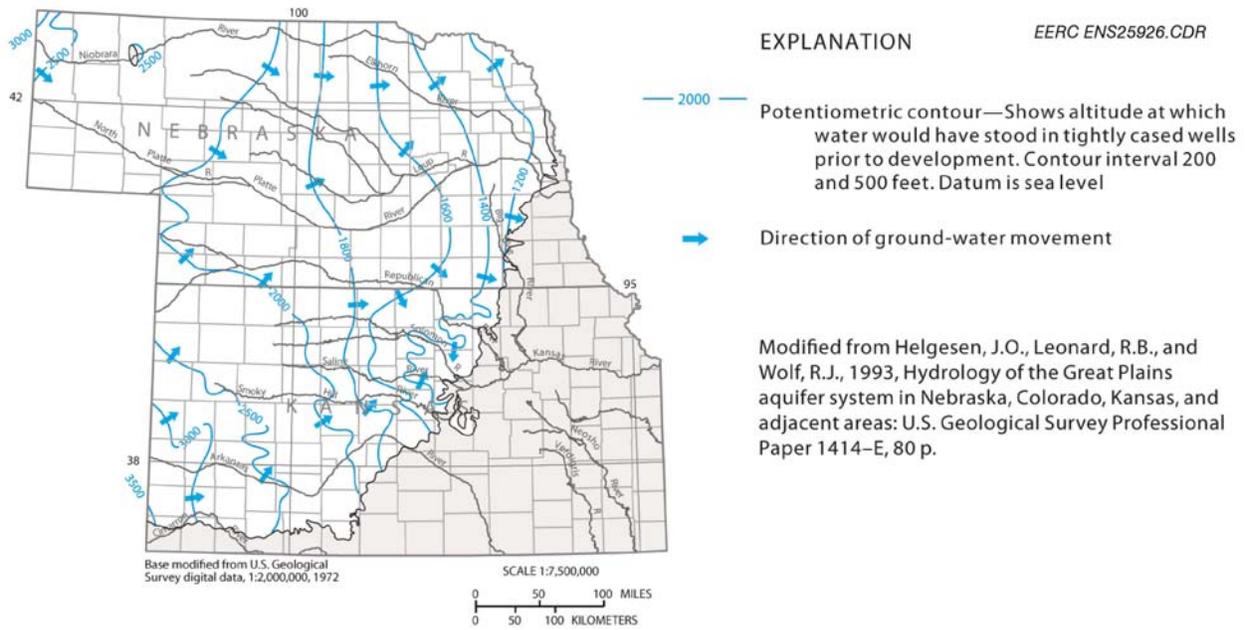
Figure 4. Generalized geohydrological section of the northern Great Plains aquifer system showing relationship of recharge, flow, leakage, and discharge.



Water moves regionally northeastward through the deeply buried lower Cretaceous aquifers. Some of the water moves hundreds of miles from aquifer recharge areas around structural uplifts on the west to discharge areas in eastern North Dakota and South Dakota.

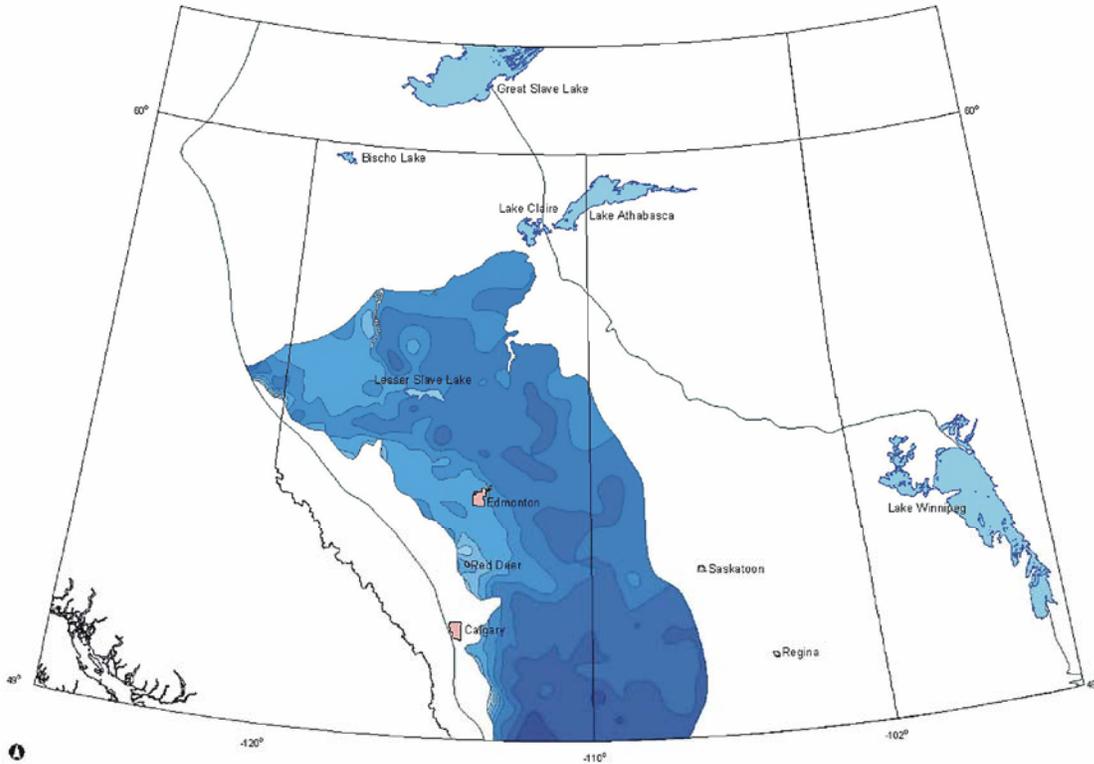
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Figure 5. Potentiometric contour map of the Lower Cretaceous aquifer system for the northern Great Plains.



Water moves generally eastward and northeast-ward in the Great Plains aquifer system. Regional movement is from areas of high water levels in southeastern Colorado to areas of low water levels in eastern Nebraska and central Kansas.

Figure 6. Potentiometric contour map of the Lower Cretaceous aquifer system in the southern PCOR Partnership region.



Legend

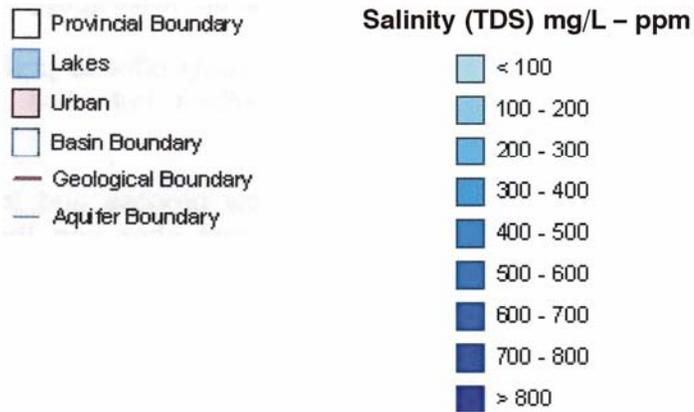


Figure 7. Freshwater hydraulic head for the Upper Aquifer unit (Viking Formation) of the Lower Cretaceous aquifer system in Alberta and Saskatchewan (Alberta Geological Survey, 2005).

As previously noted in Figure 5, in the northern U.S. portion of the region, water flow is generally to the east and northeast, and discharge from the system takes place through a number of mechanisms. Water may be discharged where the aquifer subcrops in eastern North Dakota and along the Manitoba escarpment in Canada (Figure 4). Water from the Lower Cretaceous aquifer system has also been reported in some areas to have discharged vertically and laterally through leakage into adjacent aquifers (Case, 1984; USGS PP 1402). Water is also discharged from the Lower Cretaceous aquifer system through unused wells along the Missouri and James River valleys of South Dakota (Case, 1984). These reports indicate that there are areas in the region where the Lower Cretaceous aquifer system is not closed and, therefore, may be a leakage pathway for injected CO₂. Artesian flow conditions have been historically reported in central and eastern North and South Dakota. Case (1984) suggests that potential for artesian conditions in the Upper Aquifer Unit is still present in portions of eastern South Dakota, Iowa, Minnesota, Nebraska, and North Dakota. These artesian conditions indicate that the system is under pressure, which may increase the potential for leakage into vertical fractures and improperly abandoned wellbores.

Characteristics of the Lower Aquifer Unit of the Lower Cretaceous System

The Lower Aquifer Unit was deposited in environments that included shallow marine, shoreface and deltaic swamps, as well as valley and channel fill (USGS PP 1402), Condon, 2000; Wartman, 1982; DeBruin, 1993). Sandstone is the primary lithology, with lesser amounts of siltstone, shales, and coal. Substantial reserves of coal are present in the Lower Aquifer Unit (Mannville Formation) in Alberta and Saskatchewan (Smith et al., 1994). The Mannville Formation was deposited as a clastic wedge coming off the highlands into the Alberta Basin and is significantly

thicker with a more variable lithology than its equivalents in the United States.

The thickness of the Lower Aquifer Unit varies from zero in eastern North and South Dakota where it subcrops, to over 700 feet in central Montana (USGS PP 1402). The maximum thickness of the Lower Aquifer Unit in Nebraska exceeds 400 feet; however, the typical thickness is between 100 and 200 feet. The maximum thickness in Alberta is over 2100 feet in the Rocky Mountain foothills (Hayes et al., 1994).

In the Montana and Dakota portions of the region, porosity in the Lower Aquifer Unit generally tends to be higher in the central to eastern portion of the area where the formation is shallower (USGS PP 1402). In eastern North Dakota, Kelly (1968) reports an average porosity of 42.7%. Butler (1984) reports an average porosity of 35% in eastern North Dakota to 20% in the center of the Williston Basin. In the Powder River Basin, where the Lower Aquifer Unit is more deeply buried, porosity is seldom greater than 20% (USGS PP 1402). Porosity data for the Nebraska and Canadian portions of the Lower Aquifer Unit were not readily available. However, based on their similarity with respect to deposition and lithology, it would be expected that a similar range of porosity would be found in those areas.

Permeability (the property or capacity of a medium for transmitting fluid) in the Lower Aquifer Unit can be variable. Permeability values from core measurements from a well in north-central North Dakota range from a few darcies to less than a millidarcy (NDGS Well No. 5908). Wartman (1982) reports a 20–130-ft/day range of permeability in North Dakota. Estimates of Lower Aquifer Unit intrinsic permeability for Nebraska range from approximately 10⁻¹³ ft² to over 10⁻¹⁰ ft² (Jorgensen et al., 1993).

The relationship between transmissivity and permeability is expressed in the following formula:

$$T = \frac{kpg}{\mu} h$$

Where

T = transmissivity

k = intrinsic permeability

p = density

g = gravity

μ = dynamic viscosity of fluid

h = hydraulic head

Characteristics of the Middle Aquitard Unit

The shales of the Middle Aquitard Unit are marine in origin and represent the initial widespread transgression of the Cretaceous sea onto the North American craton. The thickness (Figure 8) of the Middle Aquitard Unit may be more than 250 feet in parts of the U.S. portion of the region (USGS PP 1402; Burtner and Warner, 1984). In southern Alberta, it is reported to be approximately 115 feet thick (Reinson et al., 2004). It is absent in eastern South Dakota and part of northwest Alberta (Leckie et al., 1994). There is little information regarding the porosity and permeability of the Middle Aquitard Unit in the available literature, although Case (1984) uses a vertical hydraulic conductivity value of 1.5×10^{-11} ft/sec for the interval in South Dakota.

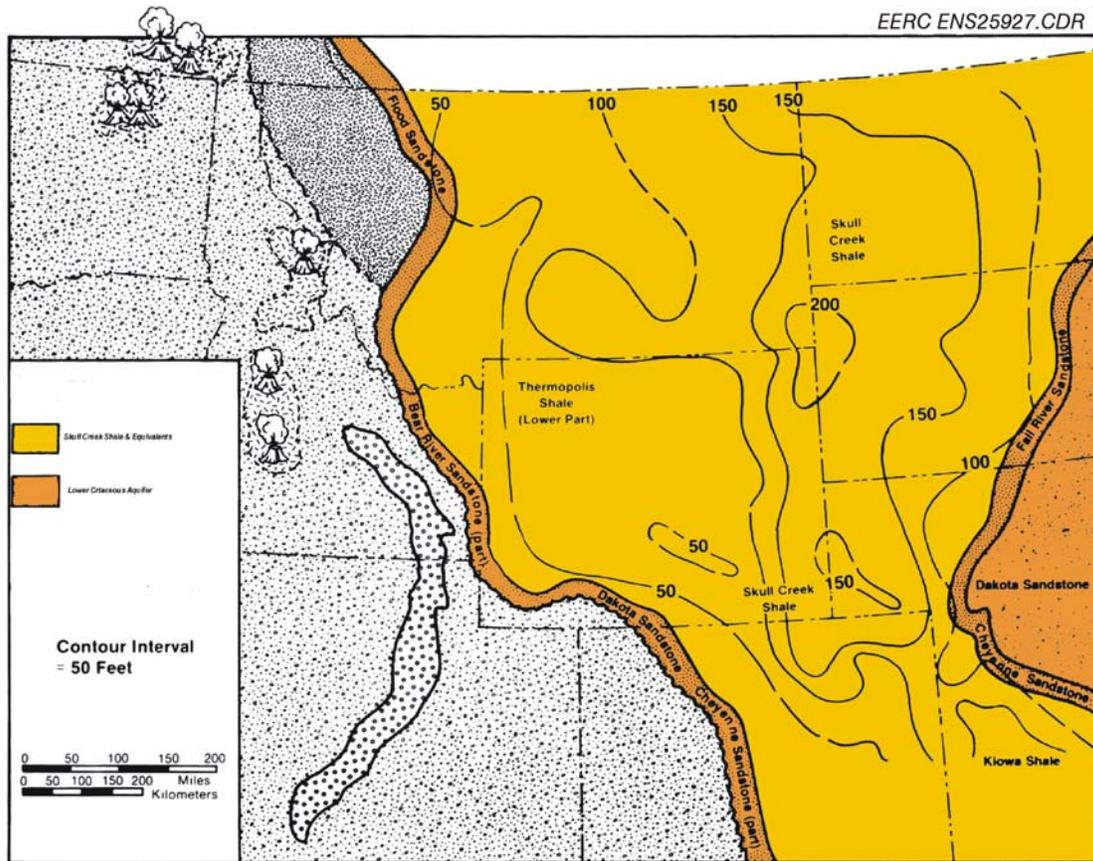
Characteristics of the Upper Aquifer Unit

Deposition of the Upper Aquifer Unit occurred in environments that ranged from marine to nonmarine (Condon, 2000; Mossop and Shetsen, 1994; DeBruin, 1993; McCloskey, 1995; LeFever and McCloskey, 1995). These environments included shallow seaways, near-shore fluvial channel systems, and deltas. The primary lithology is mudstone (Mossop and Shetsen, 1994; McCloskey, 1995). The second most common lithology is sandstone, which is typically fine to coarse grained, and massive to thinly bedded.

The thickness of the Upper Aquifer Unit ranges from zero in parts of North Dakota to several hundreds of feet in southeastern North Dakota, eastern and south-central South Dakota and north central Montana (USGS PP 1402; McClosky, 1995; Case, 1984; Condon, 2000). The Upper Aquifer Unit is absent in parts of central North Dakota. The southern portion of the unit thickens from less than 100 ft in eastern Colorado to 600 ft in northeastern Nebraska, with a small area in central Nebraska exceeding 900 ft in thickness.

There is little description of flow velocity for the Upper Aquifer Unit in the literature, but what is available suggests that it is not typically high. Hoda (1977) indicates that flow velocity in the North Dakota portion of the Upper Aquifer Unit is low, stating that in normal gravity flow areas, it does not exceed 60 ft per year, or less than 125 miles in a 10,000-year period. The Upper Aquifer Unit at locations near the Rocky Mountains, Black Hills, and other highlands may be expected to have higher flow velocities where the beds are more steeply dipping and more likely to have been fractured by orogenic activity.

Porosity (percentage of the bulk volume of a medium that is occupied by interstices) and permeability in the Upper Aquifer Unit are variable. The USGS has observed a direct relationship to porosity and sand thickness, with better porosities following thicker trends. Where developed, porosity can be good, in excess of 20% (USGS PP 1402). In south-central North Dakota, sonic log porosity can be in excess of 35% (NDGS Well No. 8826). In the Montana portion of the Powder River Basin, a porosity range from 6% to 36% has been reported (Szapakiewicz et al., 1989). With respect to permeability, in the Powder River Basin, it has been observed to range from 0.1 to 13,000 md with a geometric mean of 915 mD (Szapakiewicz et al., 1989). However, much of the formation contains mud, which can locally have an adverse effect on permeability. In Canada, more



Isopach map of the Skull Creek Shale. The base map is modified from the Geologic Atlas of the Rocky Mountain region.

Figure 7 Taken from *Burtner & Warner, 1984*

Figure 8. Isopach of the Middle Aquitard Unit (Skull Creek shale and equivalents).

than 75% of the interval is considered to have low porosity and permeability due to the presence of silt and shale (Reinson et al., 2004). In Nebraska, transmissivity values (Figure 9) can be as high as 10,000 ft²/day in areas where the unit is thick and not deeply buried (USGS Groundwater Atlas).

Water Quality of the Lower Cretaceous Aquifer System

The water quality in the Lower Cretaceous aquifer system varies greatly through the area. Water quality ranges from slightly saline to moderately saline in the Powder River and the Williston Basins (Figure 10). Freshwater is limited to recharge areas and along parts of the margin of the aquifer system. Reported TDS (total dissolved solids) values can be over 10,000 ppm in parts of the Williston basin (USGS Groundwater atlas, USGS PP 1402). Concentrations of dissolved solids increase with burial depth of the aquifer. Leakage from underlying Paleozoic saline aquifers contributes significantly to the salinity in the Lower Cretaceous aquifer.

TDS concentrations for the Upper Aquifer Unit in Nebraska (Figure 11) range from less than 1000 ppm along the southern and eastern border to over 125,000 ppm where it is deeply buried (USGS Groundwater Atlas).

In Alberta and southwestern Saskatchewan, the concentration of TDS ranges from less than 10,000 ppm (mg/L) to greater than 100,000 ppm (mg/L). The highest concentration of dissolved solids is located in a small portion of the aquifer southeast of Alberta (Figure 12).

Water quality is an important variable in evaluating the potential suitability of a saline aquifer to store CO₂. Solubility of CO₂ in formation waters is directly dependent on the total NaCl content of the system, with higher concentrations leading to lower solubility and thus negatively

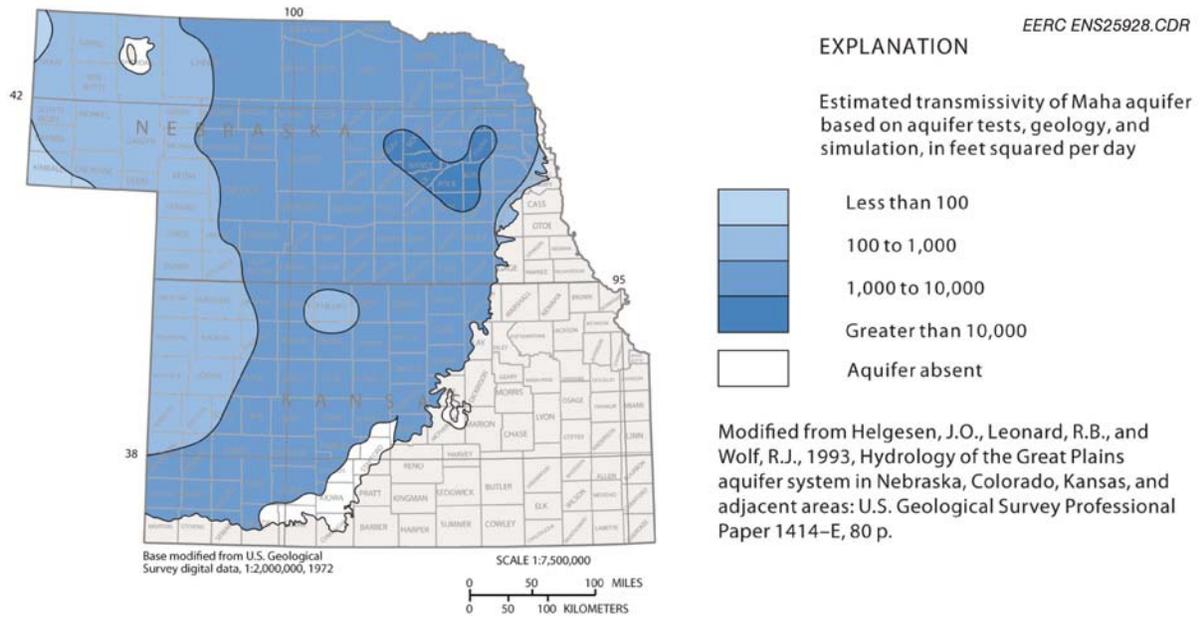
impacting the total storage capability of the aquifer. On the other hand, if salt content is low enough that the water may be used for beneficial purposes, then the aquifer would likely be precluded from being a CO₂ storage target because of the environmental regulations protecting drinking water.

Upper and Lower Seals of the Lower Cretaceous Aquifer System

The presence of competent seals both above and below an aquifer that may be used for CO₂ storage is critical to ensuring the integrity of the sink. Leakage of injected CO₂ from the target formation is undesirable for a wide variety of reasons. If the injected CO₂ is associated with a carbon credit trading market, any leakage will likely result in a decrease in the value of the credits regardless of whether or not it escapes all the way to the surface. Leakage into overlying formations may ultimately have adverse effects on overlying freshwater aquifers and the near-surface and surface environments. Leakage of saline water with dissolved CO₂ into underlying formations, while not a likely health issue, may also affect the value of any credits that may be associated with the injected CO₂.

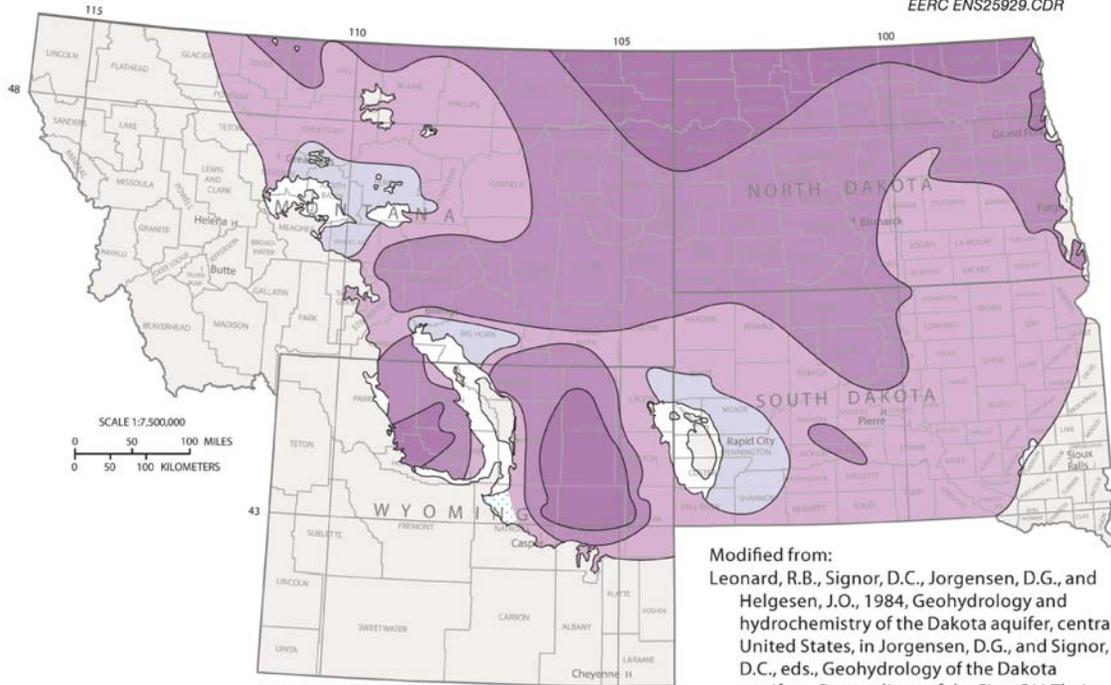
Lower Seals

In the Montana, Wyoming, North Dakota, and South Dakota portions of the PCOR Partnership region, the Lower Cretaceous aquifer system is underlain by impermeable rocks that range in age from the upper Permian through the Jurassic. The USGS formally refers to these rocks as the TK3 aquitard. In descending order, the formations included in the TK3 aquitard (USGS terminology PP 1402) are the Swift, Rierdon, Piper, Spearfish, Minnekahta, Opeche, and the upper portion of the Minnelusa. Lithologies in the underlying aquitard system vary greatly; they include sandstone, siltstones, shales, limestones, and evaporites. The evaporites include both halite and anhydrite; where present,



Transmissivity is the ease with which an aquifer will transmit water. The transmissivity of the Maha aquifer is greatest in eastern Nebraska. Low transmissivity values in the western part of the aquifer indicate that it will yield little water there.

Figure 9. Transmissivity of the Lower Cretaceous aquifer system in Nebraska.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

EXPLANATION

Dissolved-solids concentration in water from lower Cretaceous aquifers, in milligrams per liter

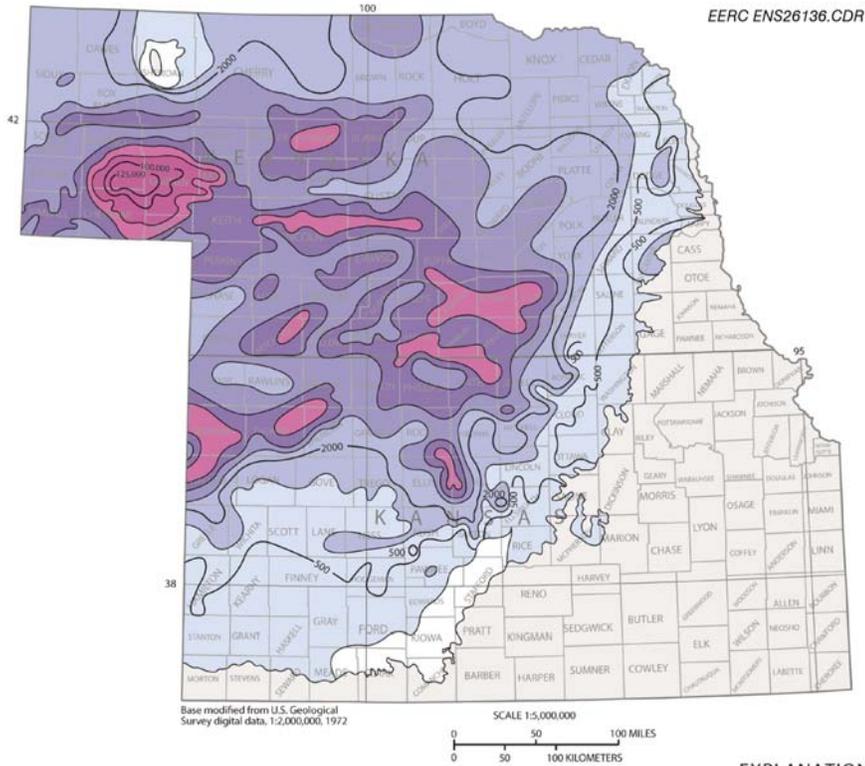
- 1,000
- 3,000
- 10,000
- No data
- Aquifers absent

Modified from:
 Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1984, Geohydrology and hydrochemistry of the Dakota aquifer, central United States, in Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. This Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 229–237.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

The lower Cretaceous aquifers contain freshwater only near where the aquifers receive recharge. Dissolved-solids concentration in the water is largest in the deep parts of the Powder River and the Williston Basins.

Figure 10. Concentration of dissolved solids in the northern Great Plains.

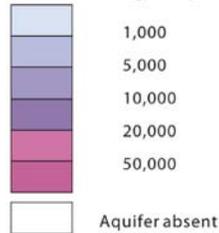


Modified from Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 1993, Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414-E, 80 p.

Freshwater occurs only along the eastern and southern margins of the Maha aquifer and in a small area in north-western Nebraska. Concentrations of dissolved solids are greater where the aquifer is confined and are very large in deeply buried parts of the aquifer.

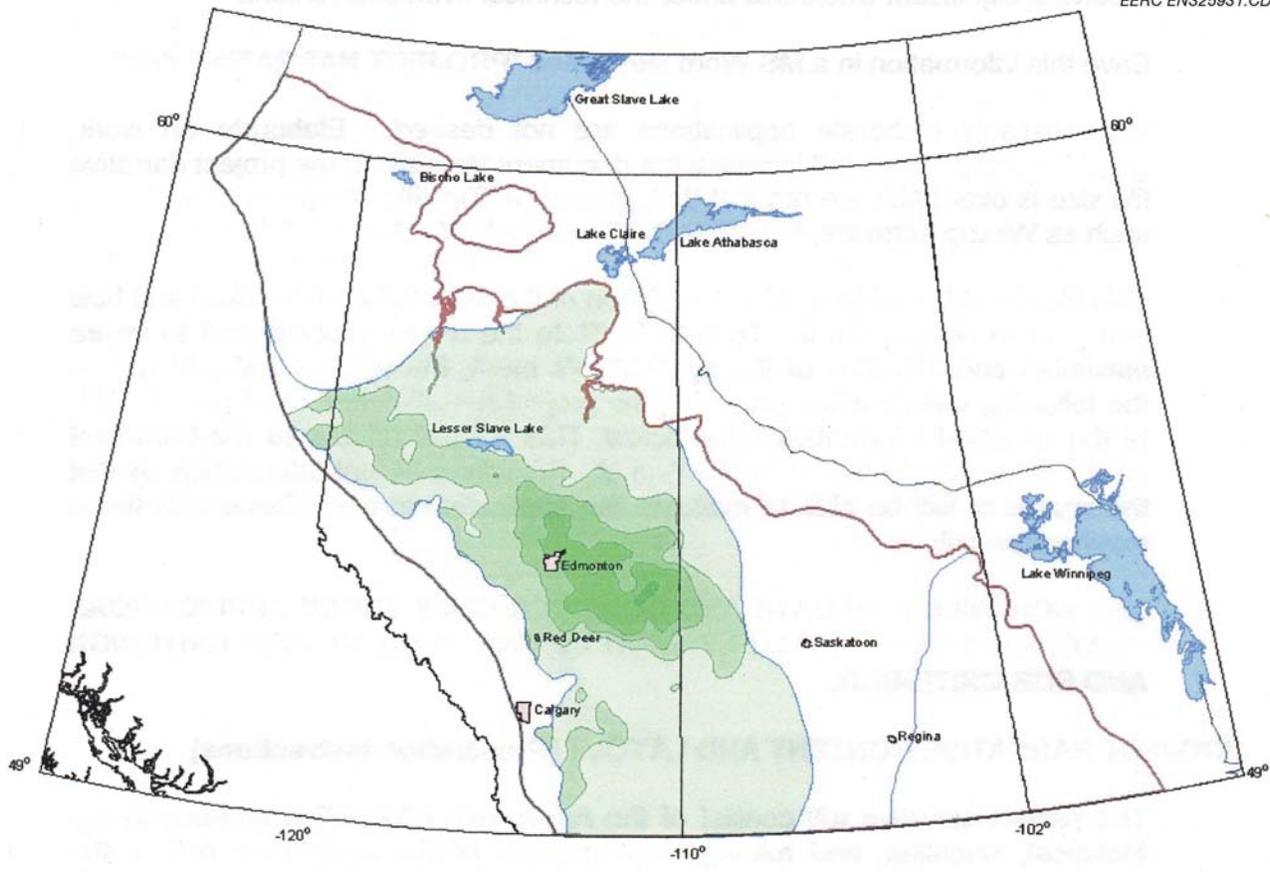
EXPLANATION

Dissolved-solids concentration in water from Maha aquifer, in milligrams per liter



— 500 — Line of equal dissolved-solids concentration—Interval, in milligrams per liter, is variable

Figure 11. Concentration of dissolved solids in Nebraska.



Legend

Provincial Boundary	Salinity (TDS) mg/L – ppm
Lakes	< 20000
Urban	20000 - 40000
Basin Boundary	40000 - 60000
Geological Boundary	60000 - 80000
Aquifer Boundary	> 80000

Figure 12. Concentration of dissolved solids for the Upper Aquifer Unit (Viking Formation) of the Lower Cretaceous aquifer system in Alberta and Saskatchewan (Alberta Geological Survey, 2005).

they form the most competent seal. The TK3 aquitard is not present everywhere, and flow into the Lower Cretaceous aquifer system from underlying sediments has been recognized (USGS PP 1402; Case, 1984). Areas where such flow has occurred could possibly provide a leakage pathway for injected CO₂ that has become dissolved. Additional detailed characterization on the competency of the TK3 aquitard should be conducted prior to any large-scale sequestration efforts.

In the Nebraska portion of the PCOR Partnership region, the Lower Cretaceous aquifer system is underlain by a series of formations making up a major confining unit that ranges in age from the Permian through the Jurassic. The USGS formally refers to this sequence as the Western Interior Plains Confining System. In descending order, the formations included in the Nebraska portion of this confining unit are the Morrison, Day Creek, White Horse, Nippewalla, Sumner Group, Chase Group, Council Grove Group, and Admire Group. The lithologies of this confining system are widely variable but include shales, limestones, and dolomites (Jorgensen et al., 1993; AAPG Geological Highway Map of the Northern Great Plains Region [Bennison and Chenoweth, 1984]). The readily available literature on this confining unit did not address the issue of flow from these units into the overlying aquifer system. Additional detailed characterization on the competency of the Western Interior Plains Confining System should be conducted prior to any large-scale sequestration efforts.

In Saskatchewan, the Lower Cretaceous aquifer system is underlain by low permeability rocks of the Mississippian–Jurassic Aquitard System. The formations that comprise this aquitard include, in descending order, the Success, Masfield, Rierdon, Upper Watrous, Lower Watrous, and Charles. The lithology of these systems includes shales, carbonates, and evaporites. In Alberta, the Lower

Cretaceous aquifer system is underlain by either sandstones or shales (Bachu, 1999).

Upper Seals

Overlying the Lower Cretaceous aquifer system in Montana, Wyoming, North Dakota, and South Dakota are impermeable rocks of the TK4 aquitard system. In ascending order, the formations that make up the TK4 are the Mowry, Belle Fourche, Greenhorn, Carlile, Niobrara, and Pierre Formations (as recognized by the USGS PP 1402 in eastern Montana and Central North Dakota and their equivalents elsewhere). Marine shale is the primary lithology of the TK4. Other lithologies include sandstone, siltstone, and chalk; there are also numerous beds of bentonite throughout parts of the section. With respect to CO₂ sequestration, the thick shales and occasional bentonite formations of the TK4 will serve as competent seals in areas where it is present.

It is important to note that the TK4 aquitard is not present throughout the entire project area. In a portion of eastern North Dakota, northwestern Iowa, western Minnesota, eastern Nebraska, and southwestern Manitoba, the TK4 is absent, and the Lower Cretaceous aquifer crops out (Anderson and Ruhl, 1984; Burkhart, 1984; Butler, 1984; Wartman, 1982; Ellis, 1982; Rutulis, 1984). Case (1984) states that the vertical hydraulic conductivity of sediments overlying the Lower Cretaceous aquifer system is variable. He suggests a range of vertical conductivities from 2×10^{-10} ft per second in eastern South Dakota, where the overlying sediments are thin, to a value of 2×10^{-11} ft per second in western South Dakota where the overburden is thicker. It is also important to note that the potential for leakage through fractures in the TK4 has been recognized (Neuzil et al., 1984; Case, 1984). Kohm and Peter (1984) discussed the relationship between leakage, fractures, and tectonically controlled lineament features in the aquitard system. Additional detailed study and

characterization of the TK4 are needed to determine its overall competency as a seal on the Lower Cretaceous aquifer system. In Nebraska, the Upper Aquifer Unit is confined by a series of shale formations including the Upper Cretaceous Graneros, Carlile, and Pierre shales, as well as the slightly permeable Tertiary clay and silt. Literature indicates that this confining system effectively restricts flow between the Lower Cretaceous aquifer system and overlying aquifers of the High Plains aquifer system at most locations (Jorgensen et al., 1993).

The Upper Aquifer Unit in the Western Canadian Sedimentary Basin is sealed by a series of rock formations referred to as the Cretaceous Aquitard System. These formations, in ascending order, are the Westgate, Fishscales, Belle Fourche, Second White Specks, Carlile, Niobrara, First White Speckled Shale, Milk River, and Pierre. These formations are primarily shales with some sands and chinks and have been identified as effective seals.

Sequestration Potential

Characteristics of the Lower Cretaceous aquifer system indicate in many locations it may be a suitable target for the large-scale injection of CO₂. Not only is this shown by examining many of the hydrogeologic characteristics, as described above, but also by considering the history of petroleum production in rock formations of the Lower Cretaceous. The existence of hydrocarbons within a geologic formation indicates that the system is closed (at least in certain locations), capable of trapping fluids and, therefore, may be suitable for long-term storage of CO₂. The examination of the hydrocarbon-producing history of a formation can be an instructive element of reconnaissance-level evaluation of aquifer systems.

The earliest produced hydrocarbons in North Dakota and South Dakota were from formations of the Upper Aquifer Unit. Specifically, natural gas was discovered in

the late 1800s in south-central North Dakota and north-central South Dakota. In this area, gas was produced from sandstones along with artesian water flow. Gas production volumes were sufficient to provide supplies to individual farms and at least one municipality, but by the early 1900s, the artesian head was depleted and most gas production ceased (Shurr, 1998). The Upper Aquifer Unit is also gas-productive in western Saskatchewan and in southern, central, and western Alberta. It is oil-productive in the Powder River Basin, southwestern Saskatchewan, and southern and central Alberta. The Lower Aquifer Unit is oil-productive in the Powder River Basin in Wyoming. Oil and gas are also produced in Lower Cretaceous formations in the southern panhandle area of Nebraska along the eastern flank of the Denver–Julesberg Basin. The sands of the Lower Aquifer Unit in Alberta and Saskatchewan are gas- and oil-productive, and they produce heavy oil. These numerous occurrences of significant hydrocarbon reservoirs are strong evidence of the capability of the Lower Cretaceous aquifer system to store large volumes of CO₂ in at least some locations.

One of the primary goals of this reconnaissance effort was to develop an estimate of the potential storage capacity of the Lower Cretaceous aquifer system. The calculated sequestration volumes determined in this study represent the Upper Aquifer Unit (Newcastle and Viking portion of the Lower Cretaceous system). This approach was used because of the greater continuity of this portion of the system with respect to the available data throughout the study area. Further research into this aquifer system is needed to evaluate the storage capacity of the Lower Aquifer System, so that the overall capacity of the entire system can be considered. The sequestration potential of Lower Cretaceous-age coals, notable in Alberta, will also need to be studied and calculated. Work should also be conducted to determine the dynamic situation that

occurs where the Skull Creek becomes absent and flow is combined from the two systems. If CO₂ is to be injected into either Upper or Lower Aquifer Units, a complete understanding of the change in water chemistry, hydrodynamics, lithology, permeability, and porosity (pore filling) will also need to be the focus of future research activities.

Water Production from the Lower Cretaceous Aquifer System

Large-scale injection of CO₂ will not be viable in areas of an aquifer that are used for water production. With this in mind, it is important to note that the Lower Cretaceous aquifer system is also an important water source at several locations in the region, especially in the southern portion (formally referred to by the USGS as the Great Plains Aquifer). In 1990, the estimated freshwater withdrawal in eastern Kansas and Nebraska from the Lower Cretaceous aquifer system was approximately 133 million gallons per day (USGS Groundwater Atlas). In Nebraska, the Lower Cretaceous aquifer system is only used as a water source in the eastern part of the state (Ellis, 1984). Through most of the rest of Nebraska, the potential productivity of the aquifer is not known. In 1981, approximately 105 million gallons of water was pumped from the Upper and Lower Aquifer Units in South Dakota (Case, 1984). These numbers reflect data only from 22 counties in South Dakota where production data were available, but they may actually be higher. As mentioned earlier, the Lower Cretaceous aquifer system is also a water source for portions of Minnesota and Iowa. Future studies must take into account the potential for beneficial use of waters within the Lower Cretaceous aquifer system, especially in the southern portions of the PCOR Partnership region.

Methodology

In order to calculate storage potentials for the Upper Aquifer Unit of the Lower Cretaceous aquifer system, a model was

developed to produce a continuous gridded surface representing the volume of CO₂ that could be sequestered per square mile. Surfaces of continuous data were generated from digitizing specific analog maps of the Williston, Powder River, Kennedy, and Alberta Basins. The natural neighbor method of grid generation was applied to the digitized data. This method was used for both interpolation and extrapolation of results, as it generally works well with clustered scattered points. In general, the model is based on existing data relating hydrological studies of regional aquifer systems, oil, gas, water well data, and existing GIS (geographic information system) map data.

The hydrological studies were developed by the USGS as part of a national effort to classify the groundwater resources of the United States. The Alberta Geological Survey completed the Canadian portion of the study in an effort to determine sequestration capacities of regional aquifer systems. The two datasets were combined to make an overall estimation of the potential storage capacity of the Lower Cretaceous aquifer system on a regional basis.

The USGS has prepared a regional reconnaissance porosity thickness and distribution map of the Newcastle Formation in the U.S. portion of the project area for net thickness of porosity. The Alberta Geological Survey has prepared a series of sequestration maps for the Viking Formation of Alberta and southwestern Saskatchewan. Understanding the distribution of porosity is a critical factor in calculating CO₂ sequestration volume. These formations are equivalent and make up the Upper Aquifer Unit of the Lower Cretaceous aquifer system. The currently available data in the U.S. portion of the project area will only allow for a rough estimation (order of magnitude) of a sequestration volume. In order to calculate more exact sequestration values, more

detailed mapping of porosity distribution will be needed.

The calculation used is a straightforward estimate that relates the pore volume in the reservoir (area × thickness × porosity) and the solubility of CO₂, in the reservoir water, at spatially varying pressures and temperatures. CO₂ solubility was corrected to account for the total salinity of the formation water.

The values obtained are limited to the nature of data that were readily available at the time of this study. For such reconnaissance-level (theoretical ultimate storage) estimations, the products created assume that all of the pore space in the system would be filled to capacity with CO₂ and the CO₂ will be soluble in the formation water according to available salinity data. This estimation will, without question, be much higher than the actual sequestration capacity.

Saline Aquifer Storage Calculation

$$Q = 7758 \times (A) \times (T) \times (\Phi) \times (CO_{2s})$$

Where:

Q = CO₂ remaining in the aquifer after injection (ft³)

$$7758 = (43,560 \text{ ft}^2/\text{acre}) \times (0.1781 \text{ bbl}/\text{ft}^3)$$

A = Area (acres)

T = Producing interval thickness (ft)

Φ = Average reservoir porosity (%)

CO_{2s} = Solubility of CO₂ (ft³/bbl)

A reconnaissance storage capacity volume of approximately 160 billion tons has been calculated for CO₂ dissolved in saline water for the Lower Cretaceous aquifer system in the PCOR Partnership region (Figure 13). Table 2 illustrates the capacities as calculated on a basinwide basis.

CONCLUSIONS

The Lower Cretaceous aquifer system may be a suitable candidate for CO₂ sequestration in some portions of the PCOR Partnership region. This study determined a storage capacity of approximately 160 billion tons throughout the region. This estimate is known to be high; however, it is to be viewed as a reconnaissance-level capacity to identify where future research efforts should be focused. In general, the aquifer system appears to be porous and permeable; the depth to access the potential sequestration interval is not overly deep; and the reservoir fluid is generally not as saline as other, deeper aquifers in the region.

Unfortunately, there are components to the aquifer that need to be more carefully studied prior to the initiation of sequestration. In parts of the region, the depth to the top of the aquifer is less than 2500 ft, the approximate depth necessary for subsurface aquifer conditions needed for storage of CO₂ in the supercritical phase. There is potential for leakage from the aquifer system at several locations, most notably where it subcrops in the east, where fracture systems have been identified, and where leakage into underlying units has been demonstrated. More detailed work on flow velocities and flow paths will be required to ensure a suitable setback from these known leakage areas is provided. It is also recommended that additional work be done on better understanding the competence of the overlying confining units to the Lower Cretaceous aquifer system.

In summary, the Lower Cretaceous aquifer system has a number of both positive and negative attributes with respect to CO₂ storage. On the negative side, these attributes and conditions may hinder the use of the Lower Cretaceous aquifer system for CO₂ storage. Perhaps the biggest hurdle is that large portions of these aquifers provide significant amounts

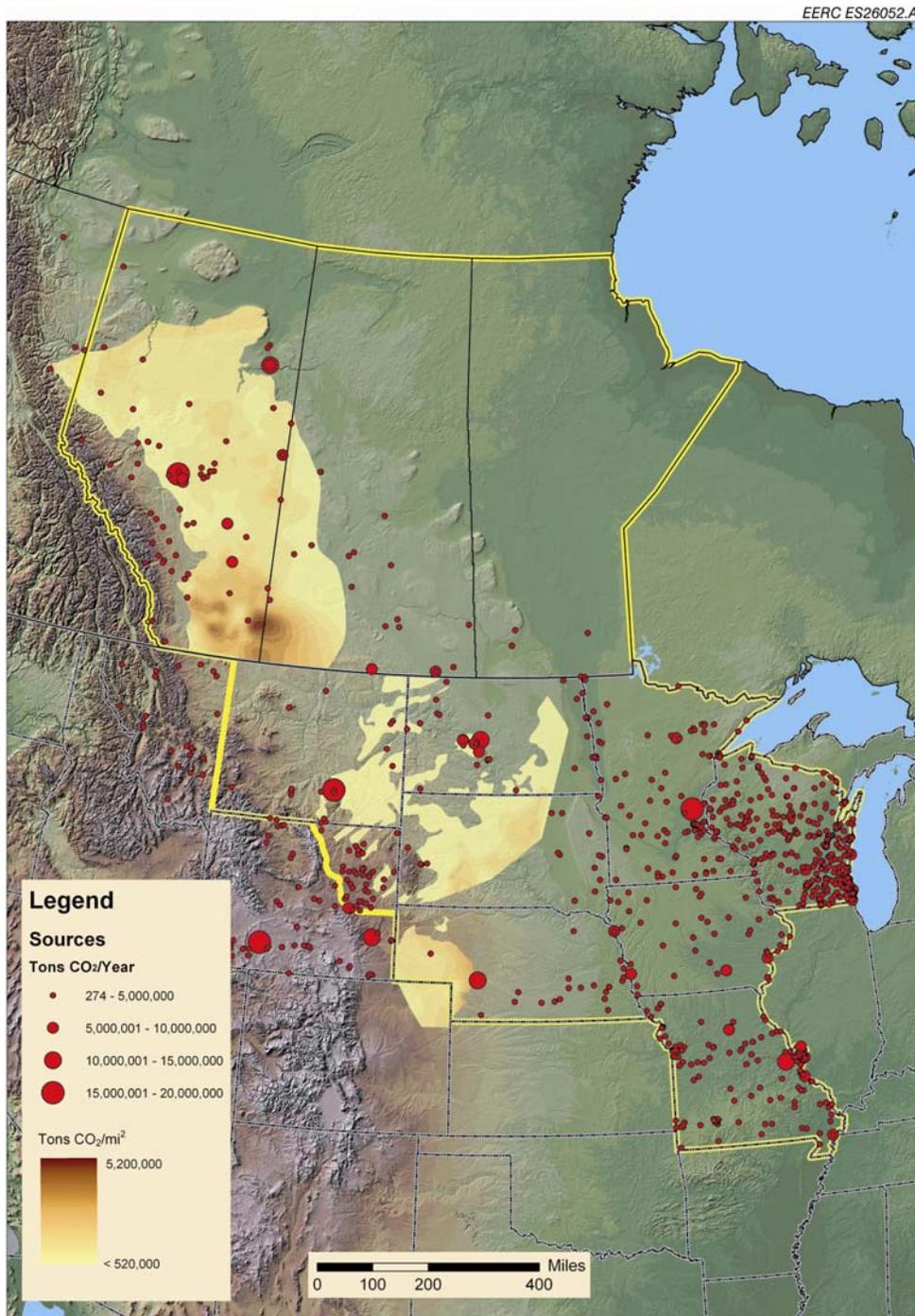


Figure 13. Reconnaissance CO₂ storage capacity volume for the Lower Cretaceous aquifer system in the PCOR Partnership region.

Table 2. Capacities as Calculated on a Basinwide Basis

Aquifer System Evaluated	Basin	Estimated CO ₂ Capacity, billion tons
Lower Cretaceous Aquifer System		10.5
Newcastle Formation	Williston and Powder River	42
Viking Formation	Alberta	100
Maha Formation	Denver–Julesberg	19

of water for irrigation, industrial, and municipal uses. The injection of CO₂ will almost certainly not be allowed into aquifers that can be used for such purposes. Other negative attributes that need to be considered include the system's shallow depth on the eastern fringes and the fact that leakage pathways have been identified (especially via underlying formations). The high transmissivity of some portions of the system will also complicate the prediction and monitoring of CO₂ plume movement.

However, on the positive side, the aquifers of the Lower Cretaceous system cover a wide portion of the PCOR Partnership region and are located proximal to many large CO₂ sources. This suggests that infrastructure needs for large-scale injection may be minimal. Large portions of the system have been demonstrated to have adequate thickness and injectivity characteristics that make it conducive to large-scale injection. The aquifers of the Lower Cretaceous are generally overlain by thick, competent seals, and significant leakage to the surface is unlikely. Finally, the Lower Cretaceous aquifer system is well studied and understood. The large body of literature available, although it is largely focused on localized aspects of the system and lacking in high-quality regionally relevant data, provides a head start on the hydrogeological characterization that would be necessary prior to implementation of large-scale CO₂ storage operations.

While general information on the structural geology, lithostratigraphy, hydrostratigraphy, and petroleum geology of the Williston Basin is readily available, additional characterization data for specific candidate sinks will be necessary before their utilization as CO₂ storage sites. Detailed maps of critical elements such as formation thickness, porosity, permeability, and water salinity will need to be developed, and the competency of regional traps will have to be further studied.

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